



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Durability of cement-stabilised rammed earth

Citation for published version:

Beckett, C & Ciancio, D 2015, 'Durability of cement-stabilised rammed earth: a case study in Western Australia', *Australian Journal of Civil Engineering*, pp. 1-9. <https://doi.org/10.1080/14488353.2015.1092671>

Digital Object Identifier (DOI):

[10.1080/14488353.2015.1092671](https://doi.org/10.1080/14488353.2015.1092671)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

Australian Journal of Civil Engineering

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



1 Durability of cement-stabilised rammed earth: A case
2 study in Western Australia

3 C.T.S. Beckett ^{1a}, D. Ciancio^a

4 ^a*School of Civil & Resource Engineering, The University of Western Australia, Perth,*
5 *WA 6009*

6 **Abstract**

Cement-stabilised rammed earth (CSRE) is a popular building material in Australia due to its natural aesthetic, good thermal properties and environmental appeal. However, little work has been done investigating the effect of long term exposure to environmental conditions on its durability. This paper presents a case study investigating the aged properties of material obtained from a 32-year old CSRE wall in Perth, WA. Core samples were obtained for unconfined compressive strength (UCS) testing and compared to results found for 28-day old specimens, manufactured using the same material and nominal compaction regime, to investigate changes in material strength over time. Sample wall sections were also obtained to determine material volume losses due to erosion. Results found for 32-year and 28-day old material are compared taking into account local climate conditions to comment on the suitability of current laboratory methods for predicting degradation of CSRE materials. Loss of strength due to exposure is found to be significant in this study. This result suggests that, when designing for the longevity of exposed CSRE materials, aging strength is an important factor that should not be neglected.

7 *Keywords:* Rammed earth, cement stabilised, durability, erosion,
8 unconfined compressive strength

9 **1. Introduction**

10 Rammed earth (RE) is a construction technique which has gained pop-
11 ularity in Australia thanks to its sustainable and aesthetic qualities. Tra-
12 ditional RE structures are formed through the compaction of raw material
13 (most commonly sandy-loam subsoil) into formwork, which is then removed
14 to allow the material to dry, granting it its considerable strength [16, 19].
15 The technique is therefore highly environmentally friendly, as the use of
16 natural materials means that little-to-no processing is required prior to con-
17 struction. The use of thick (typically 300mm) walls also grants RE structures
18 a high thermal mass, enabling them to counteract high diurnal temperature
19 fluctuations, as are common in many regions of Australia, and provide com-
20 fortable internal living environments [4]. Several examples of traditional RE
21 structures have survived for hundreds, if not thousands of years in a wide
22 range of climates of varying severity [17].

23 RE construction methods have changed little since ancient times. How-
24 ever, it is now common to add stabilising agents to the raw soil, the advan-
25 tages of which are severalfold. Primarily, the use of stabilisers significantly
26 increases material strength. Stabilised material is also far less susceptible
27 to surface wear, reducing or, ideally, eliminating the need for regular main-
28 tenance as is required for its unstabilised counterpart [14]. In addition, the

¹Corresponding author: christopher.beckett@uwa.edu.au

29 use of stabilisers also allows a wider range of soil types to be used; for ex-
30 ample, soils with lower or higher clay contents than those recommended for
31 unstabilised construction can be used if stabilised with Portland cement or
32 hydrated lime respectively [6].

33 Although the use of stabilisers for RE construction has been an accepted
34 practice in Australia over the last 30 years, the technique's youth means that
35 there is still a distinct lack of data regarding the long-term durability of these
36 materials. Current Australian RE construction guidelines [19] therefore re-
37 quire very high factors of safety for material strength in order to account
38 for any degradation that may occur, resulting in highly conservative designs
39 and, potentially, unnecessarily high construction costs.

40 This paper presents a case study conducted on material obtained from
41 a Portland cement-stabilised RE (CSRE) wall, built in 1980 in Cottesloe,
42 Perth (WA) and exposed to weathering for over 30 years. Degradation in
43 terms of both strength (unconfined compressive strength, UCS) and material
44 losses are discussed. Methods used to measure degradation in non-rammed
45 earth materials are then examined in order to determine their suitability
46 and applicability for use with CSRE when compared to results found in
47 the field. Findings are then used to identify key issues pertinent to the
48 understanding of CSRE durability and to provide guidelines for laboratory
49 testing and designers.

50 **2. RE durability: factors and assessment**

51 Durability of construction materials is the ability to withstand the de-
52 structive actions of weathering and corrosive substances without degrada-

tion. The most obvious visual sign of degradation due to weathering in RE materials is erosion. Erosion of RE materials is caused by the breakdown of interaggregate bonds (cemented or uncemented), generally provoked by moisture ingress or rain/wind pressure.

Moisture ingress affects the environment of the material clay particles producing shrinking and swelling. This is clearly of less concern for cement-stabilised materials, where the clay content is necessarily low, but is a key source of degradation in unstabilised and lime-stabilised structures [15]. Moisture ingress into porous materials can occur either through capillary suction (the migration of water due to the establishment of a pressure differential through the formation of water menisci) or through external pressure differentials arising due to incident wind [13]. The former can be controlled through the use of waterproof layers at the base of walls, for example, or by ensuring that walls remain well ventilated. The use of impermeable renders, however, to counter surface ingress has been demonstrated to result in additional degradation due to the pooling of trapped water within the material [17, 20].

Incident rainfall erodes RE materials both due to the energy released on impact and subsequent wetting. The damage caused by wind driven rain depends on a number of parameters such as the incident angle, drop size, intensity and wall surface roughness. Although intense, rainfall events are generally sufficiently short lived so that water cannot permeate the material to a significant depth; the outermost saturated material prevents additional ingress (the so-called “overcoat effect”). Saturated outer material is weaker, however, and so is prone to damage if rainfall continues at a sufficient in-

78 tensity [14]. Clearly, the effects of incident rainfall can be guarded against
79 through the proper use of wall protection, for example large overhanging
80 roof eaves [10].

81 A small number of authors have presented work investigating the dura-
82 bility of RE materials with respect to their erosion characteristics. Guettala
83 et al. [12] compared the erosion of cement and lime-stabilised earth bricks
84 (a similar material to CSRE, although not as compact) subjected to wetting
85 and drying and accelerated erosion testing [19] to that arising from exposure
86 to real climatic conditions (Biskra, Algeria). It was shown that the labo-
87 ratory tests used were too severe compared to the material aging observed
88 from real conditions, suggesting that alternative testing methods were re-
89 quired. Similarly, Hall [14] investigated erosion of CSRE walls exposed to
90 low and high velocity rainfall, at controlled pressure differentials. Results
91 showed little moisture ingress or erosion after 5 days. Although this research
92 highlighted the strengths of a suitable laboratory procedure, a link between
93 the laboratory test results and real long-term performance was beyond the
94 scope of the investigation.

95 Bui et al. [5] investigated erosion of unstabilised and hydraulic lime-
96 stabilised (5% by soil mass) RE test walls following exposure to climatic
97 weathering for 20 years. Results showed that lime-stabilised walls presented
98 little erosion (2.0mm average across the surface), whilst unstabilised walls
99 showed deeper, but still shallow erosion (6.4mm average). Results also sug-
100 gested that the exposure of larger particles (i.e. gravel) during the erosion
101 process served to protect deeper fine material from damage. This research
102 is one of the few available in the literature that provides an order of mag-

103 nitude of the erosion due to weathering of RE materials. However, any loss
104 in material strength due to aging was not assessed. Instead, it was assumed
105 that the minimal loss of wall thickness due to erosion would result in a sub-
106 sequently small loss of structural strength due to the wall’s reduced cross
107 section.

108 It is important to note that these studies could not comment on expected
109 changes in *material* strength due to aging. This paper therefore aims to ad-
110 dress this issue by determining whether any significant loss of strength occurs
111 due to exposure and to investigate methods by which it can be assessed. As
112 there are few examples of RE materials exposed to prolonged periods of
113 weathering that are able to be studied, this investigation necessarily takes
114 the form of a case study focusing on one specific site. Results found here
115 are therefore also site and material specific, but can be used to inform RE
116 design and construction practices on a larger scale.

117 **3. Aged material testing**

118 *3.1. Environment*

119 The investigated CSRE wall was built in Cottesloe, WA in 1980 and
120 demolished in early 2012. Cottesloe is classified as category [Csa] by the
121 Köppen-Geiger Climate Classification (KGCC) system (temperate, dry hot
122 summer) and as category 5 by the Australian Building Codes Board (tem-
123 perate dry, hot dry subtropical). Climatic information for this area (for
124 Swanbourne, Perth, roughly 4km North of Cottesloe) for the period 1980–
125 2013 is shown in Figure 1. These climatic conditions are comparable to many
126 areas in which RE structures are situated, so that results found here might

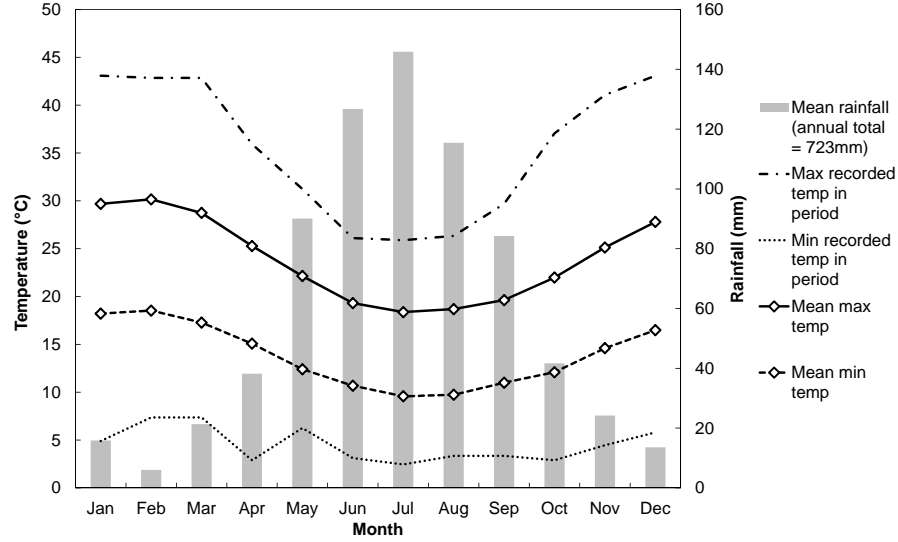


Figure 1: Mean temperature and rainfall data for Cottesloe, Perth, for the period 1980–2013 (Australian Government Bureau of Meteorology)

be extended to other RE sites in Australia and around the world [17, 2]. As the wall was situated roughly 500m from the coast, it is also possible that it was subjected to superficial salt attack; the significance of this observation will be discussed in the following sections.

3.2. Cored samples for UCS determination

A detail sketch (not to scale) showing key features around the investigated wall section is shown in Figure 2. The wall and footing was constructed from CSRE (7.5% Portland cement content by mass) to nominal widths and heights of 200mm×1800mm and 600mm×600mm respectively. A wooden trellis, anchored to the top of the wall, was provided on one side for shade,

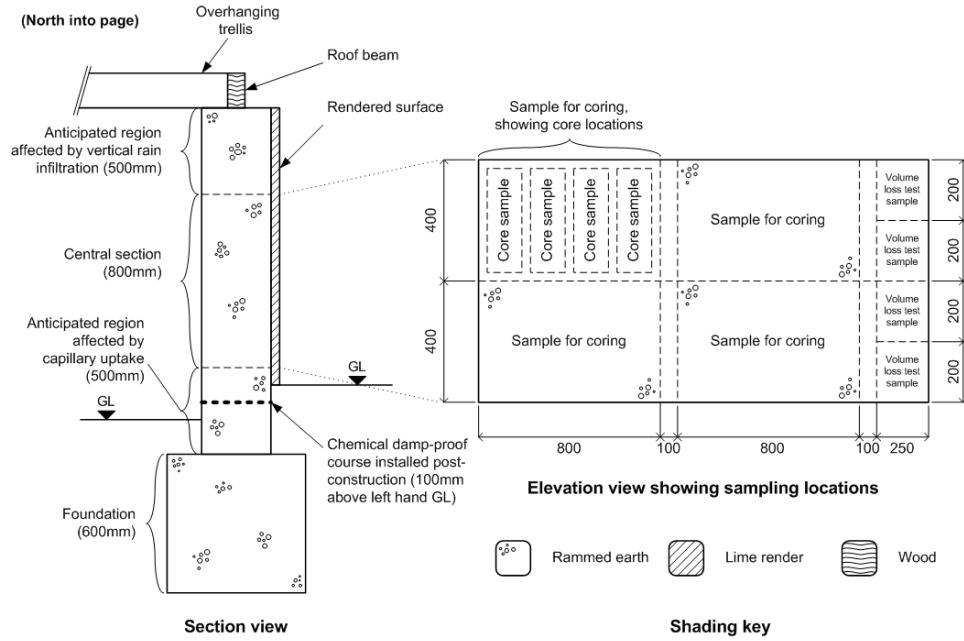


Figure 2: Sketch of key details of investigated wall (dimensions in mm, not to scale)

137 supported by a wooden roof beam. The wall was otherwise unprotected
 138 from incident rainfall. The wall ran north-south along its long axis, per-
 139 pendicular to the prevalent wind direction, but was protected from direct
 140 wind by nearby structures; gusting was, however, still possible. A chemical
 141 damp-proof course was installed in the mid 1990s, however this was unsuc-
 142 cessful due to unequal ground levels on either side of the base of the wall
 143 (as shown in Figure 2). The lower and upper 500mm portions of the wall
 144 were therefore discounted for sampling in order to avoid material too much
 145 weakened or damaged by water infiltration.

146 Four 400mm high, 800mm wide samples were obtained for coring, as
 147 shown in Figure 2, with vertical sections of 100mm width left between them
 148 to avoid damage during cutting. Four $\varnothing 100$ mm cores of nominal height

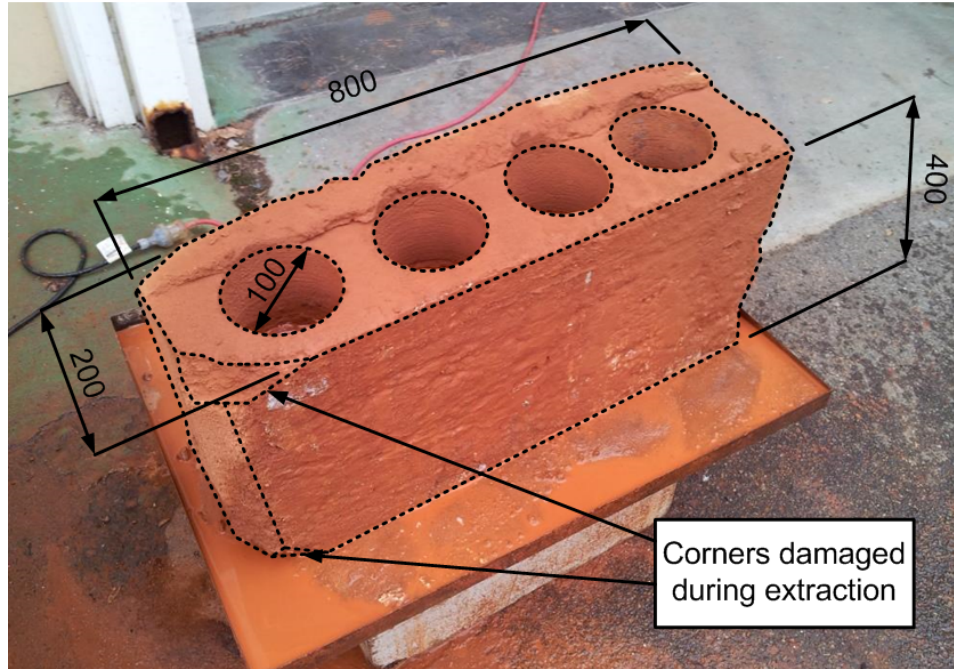


Figure 3: Extraction of cores from sample material. Outlines added for clarity. Dimensions in mm.

149 300mm were obtained for UCS testing from the central portion of each of
 150 these samples, as shown in Figure 2. An example of cored wall sample is
 151 shown in Figure 3. Cores were extracted using a water-cooled drill; coolant
 152 flow was limited in order to limit scour damage and a nominal border of
 153 50-75mm was left surrounding each core to avoid cracking the larger wall
 154 sample. Cores were left to dry to ambient conditions on wire racks and then
 155 trimmed using a dry diamond-edged cutting wheel to provide two parallel
 156 faces for UCS testing; a dry cutting wheel was used to avoid further damage
 157 to the material. Cores were then left to equilibrate to conditions of $94 \pm 2\%$
 158 relative humidity and $21 \pm 1^\circ\text{C}$ for seven days to ensure suction uniformity.

159 As the wall was constructed using ramming layers of roughly 150mm

160 compacted depth, core samples contained several such layers along their
 161 height. Some cores failed along these layer interfaces on extraction, pro-
 162 ducing shorter sections. Only 8 samples with slenderness ratio > 1.5 were
 163 therefore available for UCS testing. UCS was determined by crushing speci-
 164 mens uniaxially at a constant displacement rate of 0.3mm/min until failure.
 165 Teflon sheets were placed between the samples and the metal testing platens
 166 during testing to reduce size effects due to the slightly different slenderness
 167 ratios [7]. Failed material was then crushed, weighed and oven dried at
 168 105°C for a minimum of 48 hours to determine its water content and dry
 169 density, ρ_d .

170 3.3. Samples for volume loss testing

171 Four (nominally) 250mm wide by 200mm high sample wall sections were
 172 taken to determine volume loss due to erosion, as shown in Figure 2. A sand
 173 raining technique was used to determine the volume of these irregular sam-
 174 ples, in order to determine volume loss due to erosion. Unexposed sample
 175 surfaces (i.e. on the plane vertical and perpendicular to the viewing plane in
 176 Figure 2) were trimmed to present two parallel surfaces for placing between
 177 rigid boards. Additional boards were then used to create a tight-fitting en-
 178 closure of known volume, as shown schematically in Figure 4. Fine sand
 179 was then rained into the enclosure at a set drop height and travel speed to
 180 deposit material at an *a priori* known density. Once complete, the sample
 181 was extracted and the sand weighed in order to calculate the sample vol-
 182 ume. Volume loss was then calculated as the difference between the original
 183 and eroded volumes, where original volume was assumed to equal $b \times h \times t$

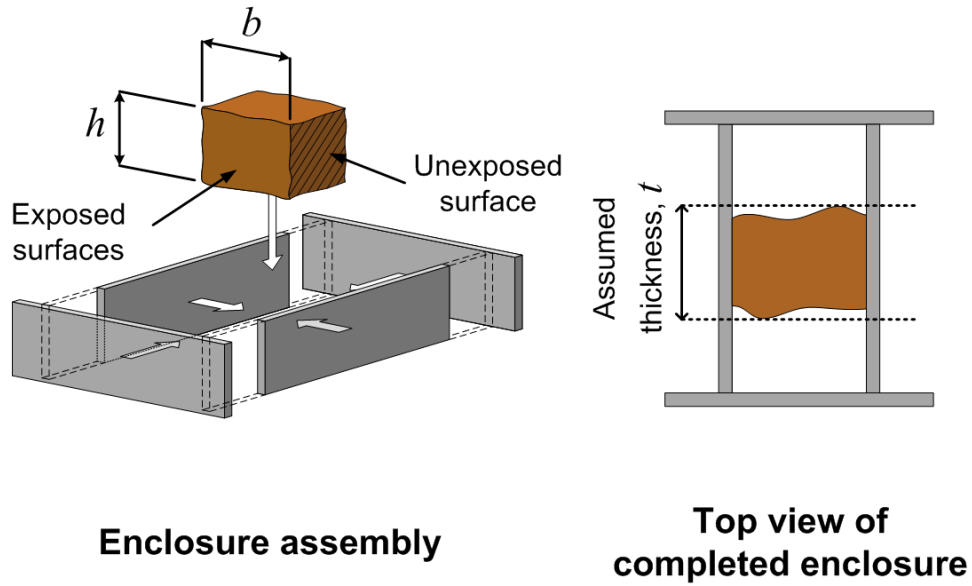


Figure 4: Assembly of enclosure for volume loss testing and principal sample dimensions

184 (i.e. the volume of the cuboid which bounds the sample's extremities) as
 185 shown in Figure 4. This assumption is reasonable as, when the wall was first
 186 constructed, the use of rigid formwork would have created smooth, parallel
 187 wall surfaces.

188 **4. Results: Aged material testing**

189 *4.1. Cored sample UCS*

190 Cored sample UCS results are shown in Figure 5 against dry density,
 191 as determined via oven drying. Linear relationships have been included to
 192 indicate the rough data trends; whether a linear relationship is the most
 193 suitable for this data is not clear, however it is sufficient to demonstrate
 194 the major differences between the different tested materials. Cored sample

slenderness ratios, given in parentheses in Figure 5, show that there is no discernable relationship between slenderness ratio and UCS, due to the use of Teflon. Results in Figure 5 for non-cored (i.e. early-age) material are discussed in Section 6.

Cored sample UCSs appear to be unchanging with changes in dry density. Other studies (e.g. Ciancio et al. [8]) have shown that the dry density of traditional and CSRE samples are affected by changes in material dry density, albeit for early-age samples (i.e. 28 days for CSRE). The apparently dry density-independent results for the 32-year old material shown in Figure 5 are therefore unusual. A potential cause might be the salt weathering phenomenon due to the proximity of the ocean to the test site; salt weathering removes hardened cement paste, weakening the major source of strength of CSRE. The 32-year old measured dry density does not therefore necessarily correlate to material strength in the same way that it might for early-age CSRE samples.

4.2. Volume loss

Sample dimensions and determined total and average volume losses for two tested wall samples are given in Table 1 (although four samples were obtained for volume loss testing, two were deemed too severely damaged by the demolition process). Average erosion depth is calculated by dividing the total volume lost by the projected exposed surface area (i.e. $b \times h$ as shown in Figure 4). Average erosion depth per year has then been calculated for 49 years (32+17) due to the addition of a protective lime render to one side of the wall 15 years after construction, as shown in Figure 2, which halted

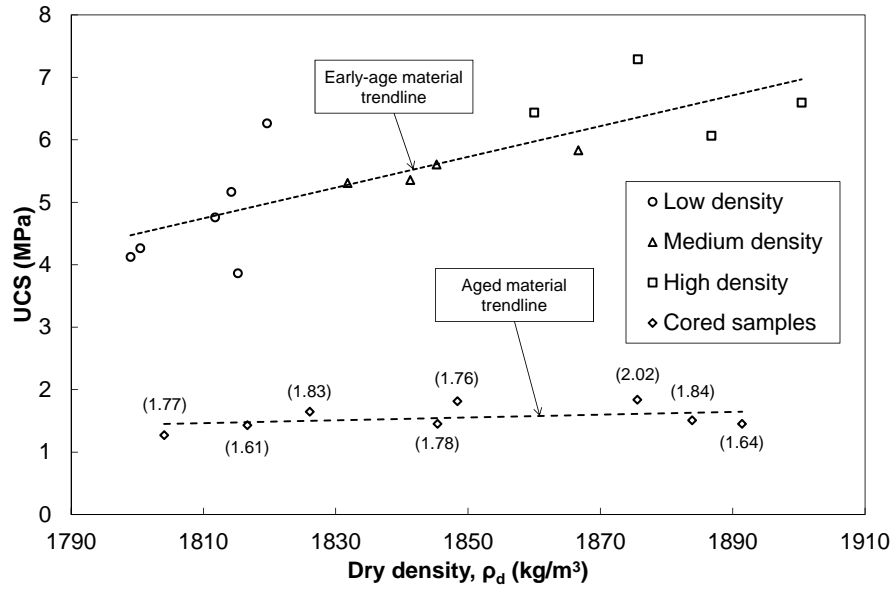


Figure 5: Core and fresh UCS results against dry density (testing and manufacture respectively). Core sample slenderness ratios are given in parentheses.

Table 1: Volume loss test results. Dimensions b , h and t as shown in Figure 4

	Specimen 1	Specimen 2	Average
Max thickness (t) (mm)	204	205	
Width (b) (mm)	320	320	
Height (h) (mm)	178	200	
Volume lost (cm ³)	426	599	
Average erosion depth (mm)	7.5	9.4	
Average erosion per year (mm/year)	0.15	0.19	0.17

erosion (on that side) from then on.

Average erosion depths of 0.15 and 0.19mm/year for the two tested samples given in Table 1 is of the same order of magnitude (0.1mm/year) of that found by Bui et al. [5]. Walls in that work were manufactured from material of similar grading to that used here, stabilised with 5% lime and subjected to a climate of similar severity (KGCC category [Dfb] (cold, warm summer), roughly 350mm rain per annum). In the absence of additional data, erosion losses of roughly 0.1mm/year could therefore offer a preliminary guide for the design of such exposed CSRE materials in mild climates. Values found for wall sample erosion are used in the following sections to calibrate erosion testing of fresh material.

5. Early-age material testing

5.1. UCS specimen manufacture

Original soil dating from the wall's construction, stored dry and unstabilised from that time, was analysed and used to prepare fresh specimens for analysis. The particle grading curve for this material is shown in Figure 6. As is typical for soils used for CSRE construction, the soil contains little clay

236 which would otherwise interfere with the cement hydration process [19].

237 Specimens for UCS testing were manufactured to reproduce material
238 properties at time of construction. Given the wide range of dry densities
239 found from cored samples (including samples of slenderness ratio < 1.5 not
240 shown in Figure 5), UCS specimens were manufactured to three different
241 target dry densities of 1825, 1875 and 1925 kg/m³ (hereafter referred to as
242 low, medium and high density specimens respectively). The use of multiple
243 dry densities allows for the unexpected result of no discernable change in
244 compressive strength with increasing dry density found for cored samples to
245 be investigated more fully.

246 Optimum water contents (OWCs) corresponding to the selected dry den-
247 sity range were determined through a combination of Modified and Standard
248 Proctor testing (MPT and SPT respectively), in accordance with AS 1289.5.2.1
249 [18]. Dry soil was combined with 7.5% Portland cement by mass to match
250 original manufacturing conditions. Linear regression through the two OWC
251 curve maxima was used to establish a rough relationship between OWC and
252 ρ_d in order to determine OWC values for target testing dry densities, as
253 shown in Figure 7 [11]. Measured and predicted OWC values are given in
254 Table 2. It is noted that the line of optimums is not expected to be lin-
255 ear; however, in the absence of additional data, a linear approximation is
256 considered to be reasonable. It is also noted that significant extrapolation
257 is required from measured results to the lowest OWC values required for
258 testing; unfortunately, lower compactive efforts were not available owing to
259 the use of standardised equipment.

260 $\varnothing 100$, 200mm tall UCS specimens were manufactured at OWC and ρ_d

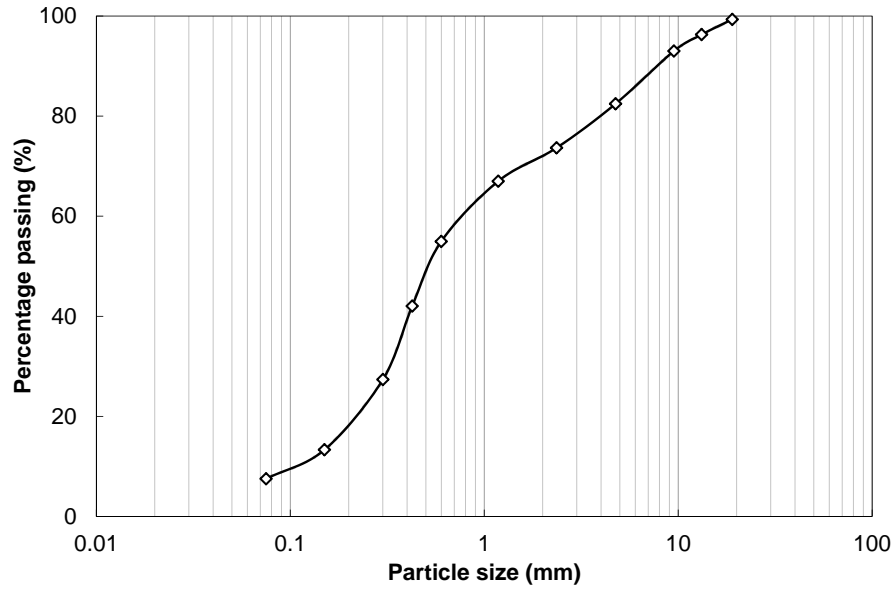


Figure 6: Original soil particle grading curve

Table 2: Measured and extrapolated OWC values

Test	MPT	SPT	1825 kg/m ³	1875 kg/m ³	1925 kg/m ³
OWC (%)	10.4	12.4	15.2	13.6	12.0

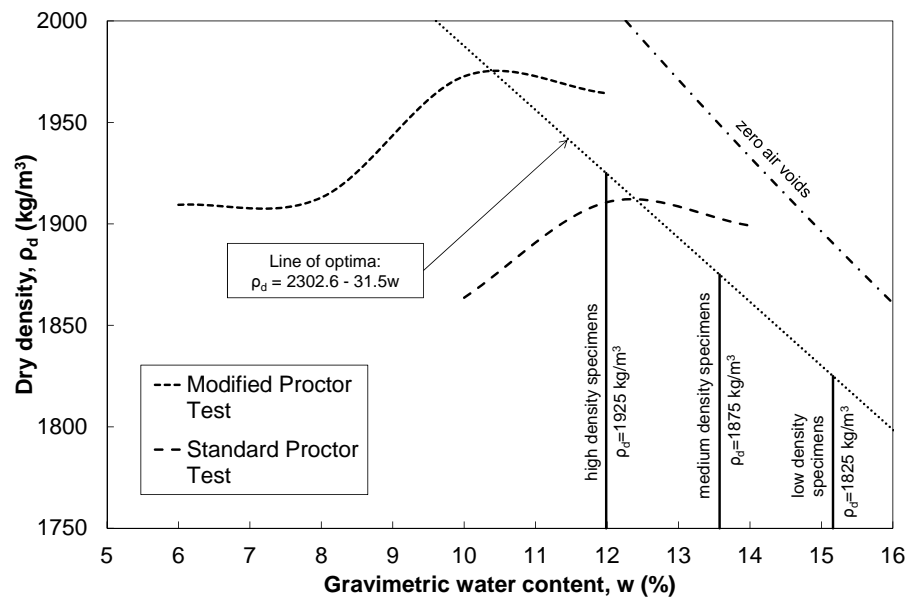


Figure 7: Compaction curves showing assumed relationship between maximum ρ_d and water content, w , and resulting OWC values for selected dry densities

261 values given in Table 2. Specimens were compacted in five layers of con-
 262 trolled mass and volume to ensure the correct compacted density [3]. A
 263 screed of material passing 1.18mm laid over the compacted surface was used
 264 to provide parallel specimen faces for testing. Specimens were extracted
 265 from the mould immediately following manufacture and cured under con-
 266 ditions of $94 \pm 2\%$ relative humidity and $21 \pm 1^\circ\text{C}$ for 28 days in order
 267 to match conditions used for cored sample equilibration. After curing for
 268 28 days, sample UCS was tested following the same procedures used for
 269 cored samples. As testing was conducted immediately, it is assumed that
 270 specimens remained equilibrated to the curing environment.

271 *5.2. Erosion and strength loss*

272 Five medium density specimens were prepared to investigate erosion and
 273 potential strength loss due to weathering; the number of specimens and
 274 densities was limited due to the lack of original material. A number of tests
 275 were considered, including the Accelerated Erosion Test (AET), the Geelong
 276 Drip Test (GDT) (both HB195, Walker and Standards Australia [19]) and
 277 wetting and drying testing (ASTM D559 [1]). The suitability of the AET for
 278 testing RE materials has recently been questioned by several authors due to
 279 its use of unrealistically high pressures [9, 12]. The GDT uses water falling
 280 dropwise onto a single spot to assess erodability, resulting in deep pitting
 281 as opposed to the more uniform erosion that is seen as a result of incident
 282 rainfall. The GDT is therefore also unsuitable to determine volume loss due
 283 to rainfall. Wetting and drying testing was therefore selected to investigate
 284 the erosion rate of laboratory-manufactured samples.

285 Although larger than specimens required by ASTM D559, cylindrical
 286 specimens for wetting and drying testing were prepared to the same dimen-
 287 sions and cured following the same procedures as used for UCS testing; this
 288 was necessary to enable the compressive strengths pre- and post-testing (the
 289 former obtained from Figure 5 for medium density specimens) to be fairly
 290 compared. Once cured, specimens were subjected to 12 test cycles, each
 291 comprising the full immersion of the specimen in room-temperature water
 292 for 5 hours followed by oven drying at $71 \pm 1^\circ\text{C}$ for 43 hours. After the
 293 final cycle was complete, specimens were re-equilibrated to conditions of 94
 294 $\pm 2\%$ relative humidity and $21 \pm 1^\circ\text{C}$ for a period of seven days prior to
 295 UCS testing (following the same procedures as described previously).

296 **6. Results: Early-age material testing**

297 *6.1. UCS testing*

298 Results for 28-day specimen UCSs are shown in Figure 5, alongside re-
 299 sults found for cored samples. Note that manufactured dry densities are
 300 slightly lower than their target values; this is due to the need to trim speci-
 301 mens to provide flush surfaces, as discussed above. Final average dry densi-
 302 ties for low, medium and high density specimens were therefore 1810 (0.8%),
 303 1846 (1.5%) and 1881 (2.3%) kg/m^3 respectively (relative error from target
 304 values in parentheses).

305 Results shown in Figure 5 suggest a linear correlation between early-age
 306 material UCS and dry density. This result is consistent with those found by
 307 previous authors (e.g. Ciancio et al. [8]) for stabilised RE materials com-
 308 pacted at their OWC. Figure 5 shows a significant difference (4 to 6 times)

309 between 28-day and cored material UCS values over the range of ρ_d tested.
310 As the same nominal compaction regime (i.e. dry density and water con-
311 tent), stabiliser type and content and equilibration conditions were used for
312 both materials, it is unlikely that these differences are due to inconsistencies
313 in material preparation. It is noted that the use of coring to obtain aged
314 material specimens could have caused damage, however it is also unlikely
315 that this action alone could lead to the large disparity in material strengths.
316 Although it is not possible to say that the observed loss of strength was
317 exclusively due to exposure, it is clear that it is a primary contributor. A
318 loss of strength on exposure is a key result for RE design and conservation
319 as it is clear that RE materials similar to that investigated in this study
320 must be protected from weathering if severe structural weakening is to be
321 avoided.

322 6.2. *Wetting and drying tests*

323 Results for changes in specimen masses during wetting and drying testing
324 (ASTM D559) are shown in Figure 8. A comparison between eroded (i.e.
325 after 12 cycles) and uncycled specimen UCS is shown in Figure 9 where
326 specimen volumes have been calculated by assuming a constant dry density.
327 Average depth of erosion and equivalent number of years for each specimen
328 are given in Table 3. Average depth of erosion has been calculated assuming
329 that degradation of the material occurred on the specimen sides only, as
330 negligible change in specimen height was found after testing. The equivalent
331 number of years has been calculated assuming an average depth of erosion
332 of 0.17mm/year, as determined from volume loss testing for aged material

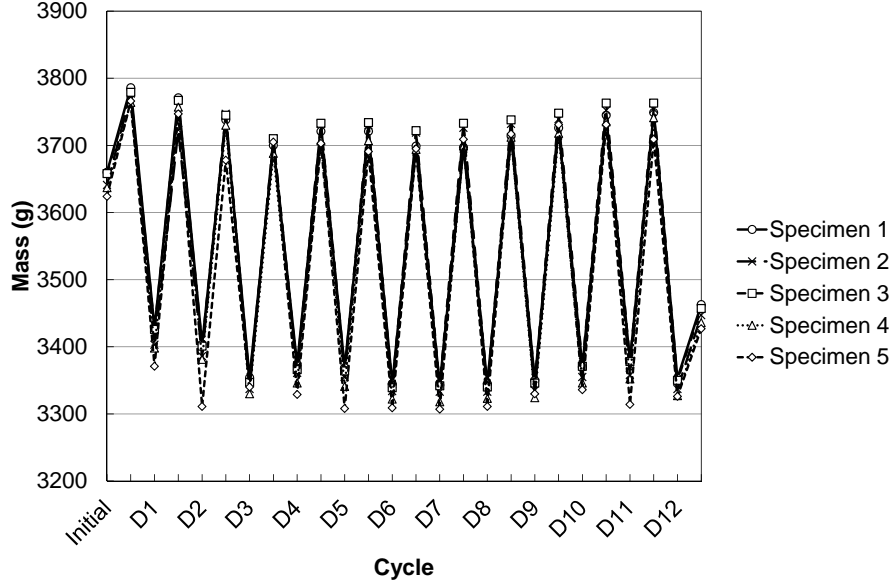


Figure 8: Changes in specimen masses on wetting and drying (“D#” represents drying cycle number)

333 (as given in Table 1).

334 Figure 8 shows that all specimens behaved similarly during wetting and
 335 drying, with the most significant mass losses occurring during the first few
 336 cycles. This is consistent with the findings of Bui et al. [5], who suggested
 337 that volume loss due to erosion is most severe on initial exposure due to the
 338 loss of poorly-bonded surface particles. Figure 8 therefore suggests that the
 339 wetting and drying test is able to reproduce erosion patterns expected of
 340 real-world conditions.

341 Results given in Table 3 suggest that one wetting and drying cycle
 342 roughly approximates material losses expected over the course of 1.5 years.
 343 This is contrary to results found by Guettala et al. [12], who suggested that

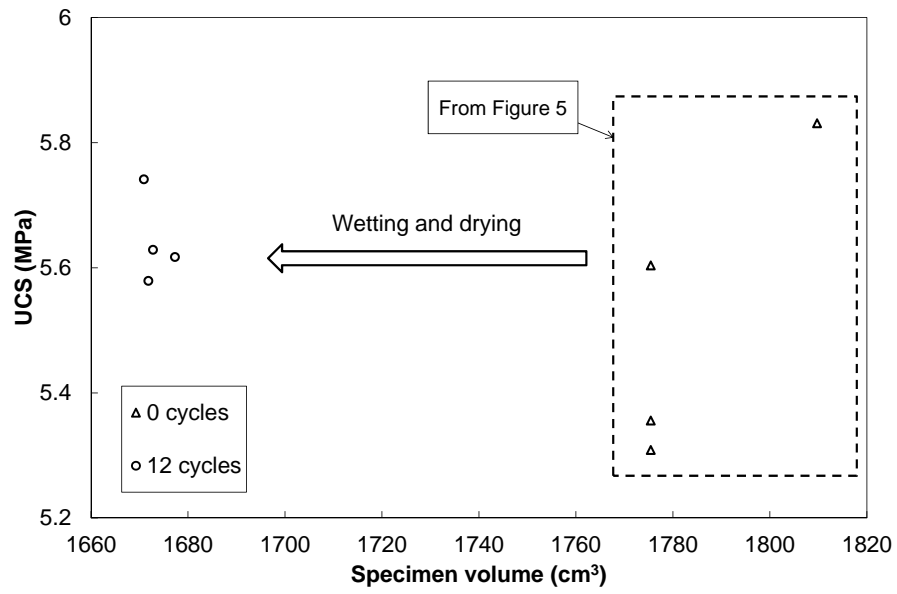


Figure 9: Wetting and drying test results for medium density specimens. The arrow represents the loss of volume associated with wetting and drying testing.

344 wetting and drying testing was too severe. It is likely, therefore, that wetting
345 and drying testing is better suited to more heavily cemented and compacted
346 materials, as used here, than those used in Guettala et al. [12]. This prelimi-
347 nary result can offer a useful rule-of-thumb for the use of wetting and drying
348 testing for determining volume loss from CSRE materials, but care should
349 clearly be taken if applying this finding to more or less heavily-cemented
350 materials.

351 Figure 9 shows that the average strengths of cycled and uncycled speci-
352 mens changed very little as a result of the wetting and drying process. This
353 result lends support to the assumption that dry density does not change
354 with exposure, used to calculate volume from mass losses, as results shown
355 in Figure 5 suggest that a change in dry density would produce a change in
356 specimen strength for early-age materials. Therefore, although the wetting
357 and drying test does result in a loss of volume, Figure 9 shows that it does
358 not adequately reproduce the changes in strength between fresh and aged
359 material seen in Figure 5. This might be due to the fact that cement bonds
360 are not affected by the short-term penetration of water unless *i)* a certain
361 amount of clay is present in the mix or *ii)* corrosive substances, for example
362 sea salt (as mentioned earlier) are contained in the water.

363 Early-age material testing has therefore demonstrated that, although
364 volume loss due to erosion can be replicated, loss in strength due to pro-
365 longed weathering could not be observed using the procedures described
366 here. This is an important result for any test aiming to accelerate the ef-
367 fects of weathering when determining CSRE durability; although aesthetic
368 effects might be accounted for, temporal effects, and subsequent structural

Table 3: Wetting and drying test results

Specimen	Number of cycles	Mass loss (g)	Volume loss (cm ³)	Average depth of erosion (mm)	Equivalent years
1	12	197	95.1	1.42	8.4
2	12	194	94.1	1.40	8.2
3	12	201	97.6	1.45	8.5
4	12	201	98.1	1.46	8.6
5	12	197	96.1	1.43	8.4

implications, are left uncertain. It is clear, then, from this case study that additional work must be conducted to determine the exact cause of, and methods to measure and guard against, degradation of CSRE materials. This is the subject of ongoing research.

7. Conclusions

This paper has discussed factors affecting the strength and durability of CSRE and results found from a case study conducted on 32-year and 28-day old CSRE material. Results from the experimental programme presented here suggested that a considerable loss of strength due to aging can occur in unprotected CSRE materials which had not been observed by previous investigators. It was also shown that changes in strength with time are not detected following accelerated wetting and drying testing. Within the limitations of the materials studied, it is therefore apparent that a weakening of the material must be accounted for when predicting the durability of exposed CSRE materials. Testing on additional materials is required, however, to extend this finding to CSRE in general.

385 The sand rainer technique provided a simple method to determine eroded
386 depths of aged samples. The average result of volume losses of 0.17mm/year
387 was similar to results found by previous authors (for climates of similar sever-
388 ity), suggesting that the preliminary values of 0.1 to 0.2mm/year represent a
389 rough guide for expected annual erosion losses for exposed CSRE materials.

390 The wetting and drying test, as described in ASTM D559, has been
391 shown to be feasible for use with the CSRE material tested here for de-
392 termining volume loss due to erosion. Volume losses equivalent of 1.5 ex-
393 posed years per cycle were found for medium density specimens, providing a
394 rough rule-of-thumb for designers and conservators. However, comparisons
395 between aged and fresh material showed that losses in strength found be-
396 tween aged and early-age material could not be reproduced, so that this test
397 cannot be used to interpret the structural implications of CSRE weathering.
398 Whether such significant losses of strength are expected of other CSRE ma-
399 terials cannot be commented on, based on the limitations of this case study.
400 However, it is clear that an assessment of expected strength loss must be
401 included in CSRE design and conservation practice; whether other “accel-
402 erated” tests can reproduce these losses is the subject of ongoing research.

403 **8. Acknowledgements**

404 The authors would like to thank the Australian Research Council and
405 the Western Australia Department of Housing for providing the funding
406 necessary to complete this work and Anderson Agusputranto for his work
407 in obtaining experimental data for this study. The work presented in this
408 paper was supported through ARC grant LP110100251.

- 409 [1] ASTM, 1996. ASTM D559-96. Standard test methods for wetting and
410 drying compacted soil-cement mixtures.
- 411 [2] Beckett, C., Augarde, C., 2012. The effect of relative humidity and tem-
412 perature on the unconfined compressive strength of rammed earth. In:
413 Mancuso, C., Jommi, C., D’Onza, F. (Eds.), *Unsaturated Soils: Re-*
414 *search and Applications*. Second European Conference on Unsaturated
415 Soils. Springer Berlin Heidelberg, pp. 287–292.
- 416 [3] Beckett, C., Ciancio, D., 2014. Effect of compaction water content on
417 the strength of cement-stabilised rammed earth materials. *Canadian*
418 *Geotechnical Journal* 51 (5), 583–590.
- 419 [4] Beckett, C. T. S., Ciancio, D., 14–16 December 2012. A review of the
420 contribution of thermal mass to thermal comfort in rammed earth struc-
421 tures. In: *Second International Conference on Sustainable Built Envi-*
422 *ronment*. Kandy, Sri Lanka.
- 423 [5] Bui, Q., Morel, J., Venkatarama Reddy, B., Ghayad, W., May 2009.
424 Durability of rammed earth walls exposed for 20 years to natural weath-
425 ering. *Building and Environment* 44 (5), 912–919.
- 426 [6] Burroughs, S., 6-9 September 2009. Recommendation for the selection
427 and stabilisation of soil for rammed earth wall construction. In: *Pro-*
428 *ceedings of the 11th International Conference on Non-Conventional Ma-*
429 *terials and Technologies (NOCMAT)*. Bath University.
- 430 [7] Ciancio, D., Gibbings, J., 2012. Experimental investigation on the com-

- 431 pressive strength of cored and molded cement-stabilized rammed earth
432 samples. *Construction and Building Materials* 28 (1), 294–304.
- 433 [8] Ciancio, D., Jaquin, P., Walker, P., 2013. Advances on the assessment of
434 soil suitability for rammed earth. *Construction and Building Materials*
435 42, 40–47.
- 436 [9] Cid-Falceto, J., Mazarrón, F. R., Cañas, I., 2012. Assessment of com-
437 pressed earth blocks made in Spain: International durability tests. *Con-*
438 *struction and Building Materials* 37, 738–745.
- 439 [10] Easton, D., 2007. *The Rammed Earth House, Completely Revised Edi-*
440 *tion*. Chelsea Green Publication Company, Vermont (USA).
- 441 [11] Fredlund, D., Rahardjo, H., 1993. *Soil mechanics for unsaturated soils*.
442 John Wiley & Sons Inc., New York (USA).
- 443 [12] Guettala, A., Abibsi, A., Houari, H., Apr. 2006. Durability study of
444 stabilized earth concrete under both laboratory and climatic conditions
445 exposure. *Construction and Building Materials* 20 (3), 119–127.
- 446 [13] Hall, C., Kalimeris, A. N., 1982. Water-movement in porous building-
447 materials—5. absorption and shedding of rain by building surfaces.
448 *Building and Environment* 17 (4), 257–262.
- 449 [14] Hall, M. R., 2007. Assessing the environmental performance of sta-
450 bilised rammed earth walls using a climatic simulation chamber. *Build-*
451 *ing and Environment* 42 (1), 139–145.

- 452 [15] Jaquin, P., Augarde, C. E., 2012. Earth building: History, science and
453 conservation. IHS BRE Press (UK).
- 454 [16] Jaquin, P. A., Augarde, C. E., Gallipoli, D., Toll, D. G., 2009. The
455 strength of unstabilised rammed earth materials. *Géotechnique* 59 (5),
456 487–490.
- 457 [17] Jaquin, P. A., Augarde, C. E., Gerrard, C. M., 2008. A chronological
458 description of the spatial development of rammed earth techniques.
459 *International Journal of Architectural Heritage: Conservation, Analysis*
460 *and Restoration* 2 (4), 377–400.
- 461 [18] SA, 2003. AS1289.5.2.1.-2003. Methods of testing soils for engineering
462 purposes. Method 5.2.1: Soil compaction and density testsDetermination
463 of the dry density/moisture content relation of a soil using modified
464 compactive effort.
- 465 [19] Walker, P., Standards Australia, 2002. HB 195: The Australian Earth
466 Building Handbook. SAI Global Ltd., Sydney, Australia.
- 467 [20] Young, D., 2008. Salt attack and rising damp: A guide to salt damp
468 in historic and older buildings. Tech. rep., Heritage Council of NSW,
469 Heritage Victoria, South Australian Department for Environment and
470 Heritage, Adelaide City Council.